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A Luminance Compensation Method Using Optical Sensors with Optimized Memory Size for High Image Quality AMOLED Displays

Kyonghwan Oh, Seong-Kwan Hong, and Oh-Kyong Kwon*

Department of Electronic Engineering, Hanyang University, Seoul 04763, Korea

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This paper proposes a luminance compensation method using optical sensors to achieve high luminance uniformity of active matrix organic light-emitting diode (AMOLED) displays. The proposed method compensates for the non-uniformity of luminance by capturing the luminance of entire pixels and extracting the characteristic parameters. Data modulation using the extracted characteristic parameters is performed to improve luminance uniformity. In addition, memory size is optimized by selecting an optimal bit depth of the extracted characteristic parameters according to the trade-off between the required memory size and luminance uniformity. To verify the proposed compensation method with the optimized memory size, a 40-inch 1920×1080 AMOLED display with a target maximum luminance of 350 cd/m^2 is used. The proposed compensation method considering a 4σ range of luminance reduces luminance error from ± 38.64%, ± 36.32%, and ± 43.12% to ± 2.68%, ± 2.64%, and ± 2.76% for red, green, and blue colors, respectively. The optimal bit depth of each characteristic parameter is 6-bit and the total required memory size to achieve high luminance uniformity is 74.6 Mbits.

Keywords : AMOLED displays, Luminance compensation, Optical sensors, Image quality
OCIS codes : (120.2040) Displays; (100.2980) Image enhancement; (100.3010) Image reconstruction techniques

I. INTRODUCTION

Active matrix organic light-emitting diode (AMOLED) displays are widely used for flat panel display applications due to several advantages such as high contrast ratio, fast response time, and high flexibility. Thus, the market for commercial products using AMOLED displays is continuously increasing, but mass production of large-sized AMOLED displays such as televisions still falls short of expectations. The most critical issue for large-sized AMOLED displays is non-uniformity of the luminance caused by variations or shifts in the electrical characteristics of thin film transistors (TFTs) such as low temperature polycrystalline silicon (LTPS) TFTs and indium gallium zinc oxide (IGZO) TFTs.

To overcome the aforementioned problems, several studies on various driving methods have been reported [1-14]. Internal compensation methods [1-7] perform compensation in pixel structures by storing a threshold voltage (V_{th}) variation of TFTs to a capacitor in the pixel and then compensate for the emission current using a stored V_{th} variation. However, as the display resolution increases, the row line time decreases; thereby, the luminance uniformity becomes degraded because the compensation is performed during a row line time.

External compensation methods [8-12] perform compensation using external sensing circuits, compensation logic circuits, and external memory with a simple pixel structure. These methods extract the electrical characteristic parameters of TFTs by sensing the voltage or current of TFTs. As the display resolution and efficiency of organic light-emitting diodes (OLEDs) increase for a given panel size, the sensed current of TFTs decreases. Accordingly, sensing operations require highly accurate analog-to-digital converters and take a long settling time of the voltage or current of TFTs. Moreover, the sensing circuits and system architectures for the external compensation method should be repeatedly modified according to the type of TFT and optoelectronic

*Corresponding author: okwon@hanyang.ac.kr
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characteristics of OLEDs.

Compensation methods using optical sensors [13, 14] compensate for both the electrical and optical characteristics of AMOLED pixels. The luminance model for each pixel in [13] has a quadruple relationship between the input gray and output luminance. However, this model is inaccurate because the drain current of the TFT is not quadrupled according to the input gray level [16, 17]; moreover, the luminance of the OLED according to the drain current of the TFT is not linear. To reflect more realistic optoelectronic characteristics of AMOLED pixels, a compensation method with a modified model [14] is reported. Although this method achieves good luminance uniformity, it requires a lot of memory resources to store the characteristic parameters. Since the required memory for compensation linearly depends on the number of pixels of AMOLED panel, memory optimization is essential to reduce the required memory size for high-resolution AMOLED displays. Since compensation methods using optical sensors initially compensate for the non-uniformity of luminance only once, these methods are suitable for AMOLED displays using LTPS TFT backplanes due to the good long-term stability of LTPS TFTs. However, these methods suffer from electrical characteristic shifts of TFTs during display operation for AMOLED displays using IGZO TFT backplanes.

In this paper, we propose a luminance compensation method using optical sensors with a simplified compensation model equation to achieve high image quality AMOLED displays using an LTPS TFT backplane. Moreover, the required memory size is optimized to maintain the high luminance uniformity of the AMOLED displays by analyzing the trade-off between the required memory size and luminance uniformity. To verify the proposed compensation method with the optimized memory size, a 40-inch 1920×1080 AMOLED display panel is used.

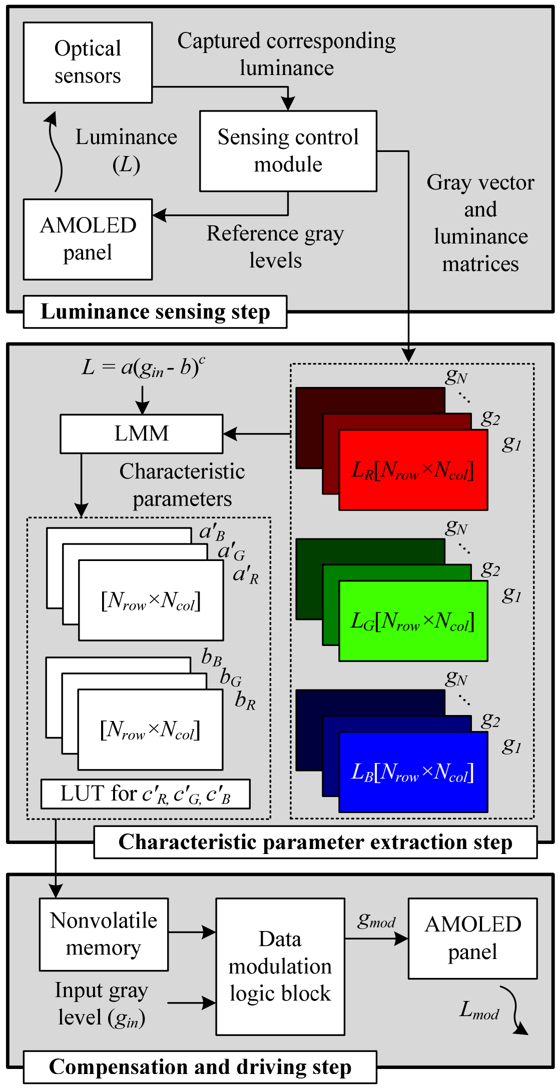


FIG. 1. The three steps of the proposed luminance compensation method.

II. THE PROPOSED LUMINANCE COMPENSATION METHOD

As shown in Fig. 1, the proposed luminance compensation method consists of three steps, which include a luminance sensing step, a characteristic parameter extraction step, and a compensation and driving step.

In the luminance sensing step, the sensing control module applies the reference gray levels to each pixel in the AMOLED panel, and then the optical sensors such as charge-coupled devices and CMOS image sensors capture the luminance of the pixel. The reference gray levels, which are selected to characterize luminance according to input gray level of each pixel, can be expressed as a gray vector $G_{ref} = \{g_1, g_2, \ldots, g_N\}$, where g_i is the ith reference gray level, and N is the number of reference gray levels. The captured luminance can be represented as L_R, L_G, and L_B, which are luminance matrices with a dimension of $N_{row} \times N_{col} \times N$ for red, green, and blue colors, respectively, where N_{row} and N_{col} are the numbers of row lines and column lines of the AMOLED displays, respectively. The gray vector and the captured luminance matrices are transferred to the next step.

In the characteristic parameter extraction step, the characteristic parameters are extracted for each pixel. The luminance model for the characterization [13] is given by

$$L = a\left(g_{in} - b\right)^c, \tag{1}$$

where L, a, g_{in}, b, and c are luminance of the pixel, slope parameter, input gray level, shift parameter, and curvature parameter, respectively, assuming that $g_{in} \geq b$, otherwise $L = 0$. Since (1) is a general representation of the relation between luminance and input gray level, it can be used for any pixel circuits and driving method for AMOLED displays.

The Levenberg-Marquardt method (LMM) [15], which is known as an algorithm for nonlinear least square curve-fitting problems, is employed to extract the characteristic parameters using gray vector and luminance matrices. Parameters a and b are represented as $N_{row}\times N_{col}$ matrices, and parameter c is simplified as a constant for each color, as described in [13]. Since the characteristic parameter extraction step requires many iterative calculations to employ the LMM for each pixel, it takes a relatively long time compared to the other two steps, but is performed only once for each panel. Parameters a and c are preprocessed to a' and c' with look-up table (LUT), respectively, in order to simplify the data modulation logic, which will be described in the next step.

In the compensation and driving step, g_{in} is modulated to compensate for the non-uniformity of luminance using the data modulation logic block, such that the luminance can be independent of the pixel characteristics. The modulated gray data (g_{mod}) can be expressed as

$$g_{mod} = b + \left(\frac{L_{MAX}}{a} \left(\frac{g_{in}}{255} \right)^{\gamma} \right)^{1/c}, \tag{2}$$

where L_{MAX} and γ are target maximum luminance and panel gamma for gamma correction, respectively. By applying g_{mod} in (2) to g_{in} in (1), the compensated luminance (L_{mod}) can be expressed as

$$L_{mod} = L_{MAX} \left(\frac{g_{in}}{255} \right)^{\gamma}, \tag{3}$$

showing that L_{mod} is independent of the characteristic parameters. Thus, the proposed method improves the luminance uniformity of the AMOLED panel regardless of variation in the luminance characteristics of each pixel. To simplify the data modulation logic block and optimize the required bit depth of the parameters, g_{mod} in (2) is rearranged to

$$g_{mod} = b + \left(\frac{L_{MAX}}{a} \right)^{1/c} \left(\frac{g_{in}}{255} \right)^{\gamma/c}. \tag{4}$$

By substituting a' and c' for $(L_{MAX}/a)^{1/c}$ and γ/c in (4), respectively, g_{mod} can be given by

$$g_{mod} = b + a' \left(\frac{g_{in}}{255} \right)^{c'}. \tag{5}$$

The parameters a', b, and c' for each color, which are preprocessed in the characteristic parameter extraction step, are stored in nonvolatile memory (NVM) on the display module. Figure 2 shows the system block diagram for the proposed compensation method, which includes the timing

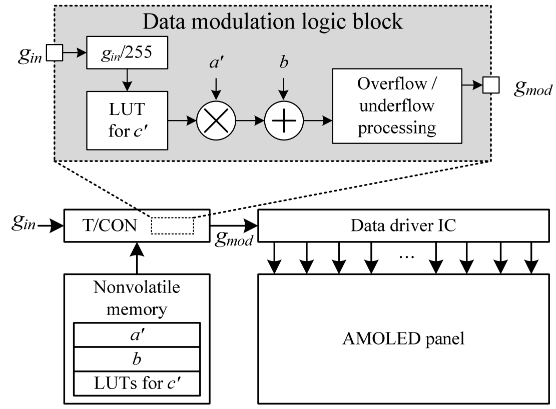


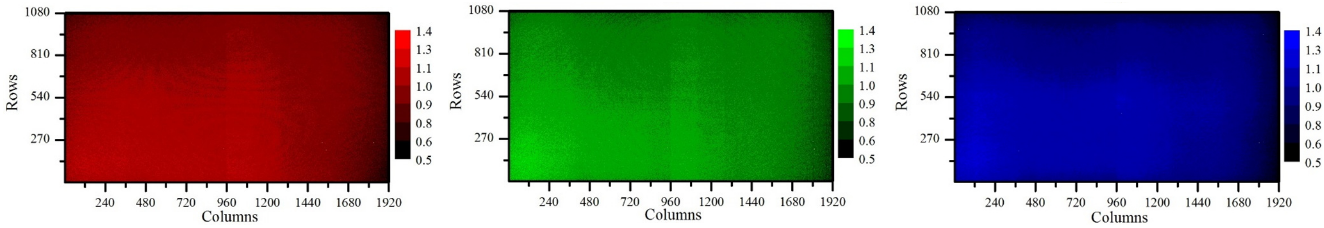
FIG. 2. System block diagram of the proposed method with a data modulation logic block.

controller (T/CON) comprising the data modulation logic block using a simple arithmetic logic circuit.

III. OPTIMIZATION OF REQUIRED MEMORY SIZE FOR THE PROPOSED COMPENSATION METHOD

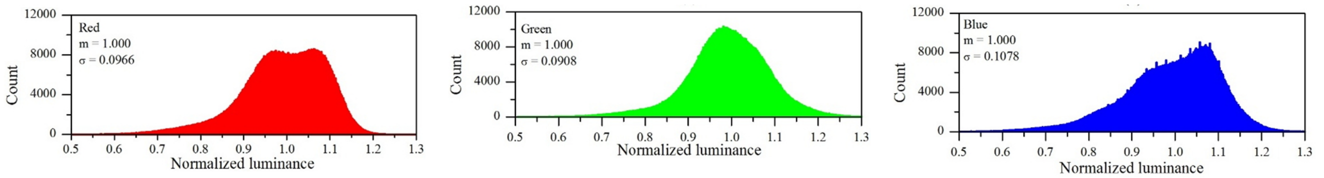
A 40-inch 1920×1080 AMOLED panel using an LTPS TFT backplane is used to verify the proposed compensation method and optimize the required memory size according to the luminance uniformity. A display module incorporating 8-bit data driver ICs is used with the maximum output analog voltage representing the nominal maximum luminance. The target maximum luminance for red, green, and blue colors are 74.4 cd/m^2, 250.3 cd/m^2, and 25.3 cd/m^2, respectively, resulting in a total maximum luminance of 350 cd/m^2. The panel gamma for gamma correction is set to 2.2, and a gray vector (G_{ref}) of {31, 63, 127, 190, 255} is used to extract the characteristic parameters. To acquire the screen image, we use Vieworks VA-29MC-M/C5^{TM} camera which adopts a monochrome charge coupled device (CCD) sensor with a resolution of 29 Mpixel (6576×4384). Before capturing the luminance of the AMOLED panel, we calibrate the image sensor by using a sheet light source with high-uniformity to compensate for pixel-to-pixel variation of the CCD. The camera and AMOLED panel are accurately aligned and positioned by displaying the marker images on the AMOLED panel. The aligned camera is used to capture the image of a single pixel of the AMOLED panel by using 3×3 pixels of the CCD. The image with a resolution of 5760×3240 is extracted from the captured image, and then scaled by 9:1 using spatial averaging to convert the captured image into the image with a display's resolution of 1920×1080. The LMM is calculated using a personal computer, and the data modulation logic block and T/CON are implemented using a field-programmable gate array.

Figures 3 and 4 respectively show the measured normalized



(a) (b) (c)

FIG. 3. The measured normalized luminance of each pixel at the 190th gray level without the proposed compensation method for (a) red, (b) green, and (c) blue colors.



(a) (b) (c)

FIG. 4. Histograms of the measured normalized luminance of the panel at the 190th gray level without the proposed compensation method, where the average luminance is the target maximum luminance for (a) red, (b) green, and (c) blue colors.

luminance of each pixel and histograms of the measured normalized luminance of the panel at the 190th gray without the proposed compensation method. The standard deviations (σ) of the normalized luminance are 0.0966, 0.0908, and 0.1078 for red, green, and blue colors, respectively. The luminance error within the 4σ range of the luminance, which includes 99.99% of samples for a normal distribution, are ± 38.64%, ± 36.32%, and ± 43.12% for red, green, and blue colors, respectively.

To compensate for the non-uniformity of luminance, characteristic parameters are extracted for each color. Figure 5 shows the histograms of the extracted *a'* and *b*. The average values and standard deviations of *a'* are 1.0364 and 0.0965, 0.8648 and 0.0811, and 0.1962 and 0.2167 for red, green, and blue, respectively. The average values and standard deviations of *b* are 7.2052 and 3.3583, 4.8415 and 3.3050, and 8.0156 and 3.0086 for red, green, and blue colors, respectively.

The above extracted characteristic parameters are quantized using bit depth, which is determined for the appropriate memory size of the NVM, and stored in the NVM. As the bit depth of the characteristic parameters increases, the luminance error decreases, which results in improving the luminance uniformity, but the system cost increases. Therefore, an optimal bit depth of the characteristic parameters should be selected to achieve an acceptable luminance uniformity.

The maximum and minimum values for quantizing the characteristic parameters, of which the differences represent the range of characteristic parameters for compensation, should be determined according to $N_c\sigma$ of the extracted characteristic parameters, where N_c is a variable to select the distribution range of the characteristic parameters for

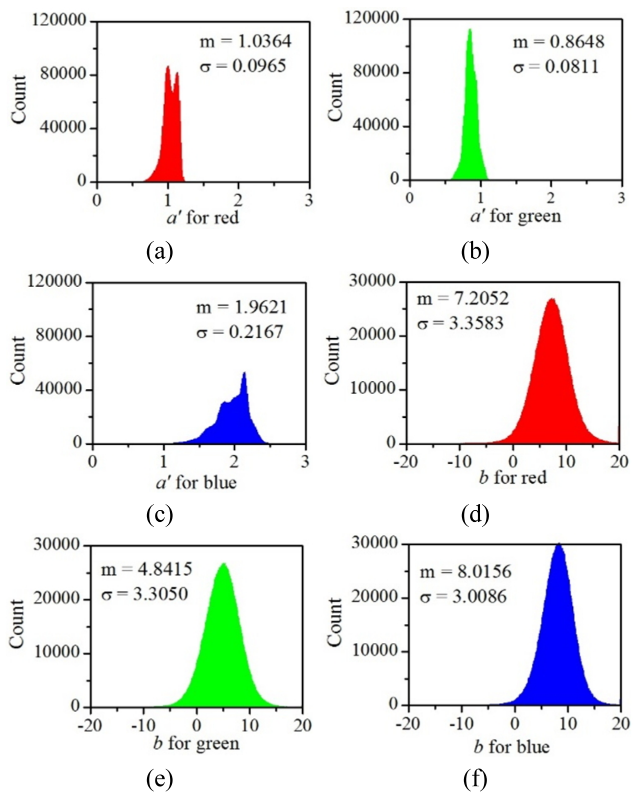


FIG. 5. Histograms of the extracted *a'* for (a) red, (b) green, and (c) blue colors and *b* for (d) red, (e) green, and (f) blue colors.

compensation. Luminance errors according to bit depth for each N_c are measured to determine the optimal bit depth of each characteristic parameter. Figure 6 (a) and (b) show

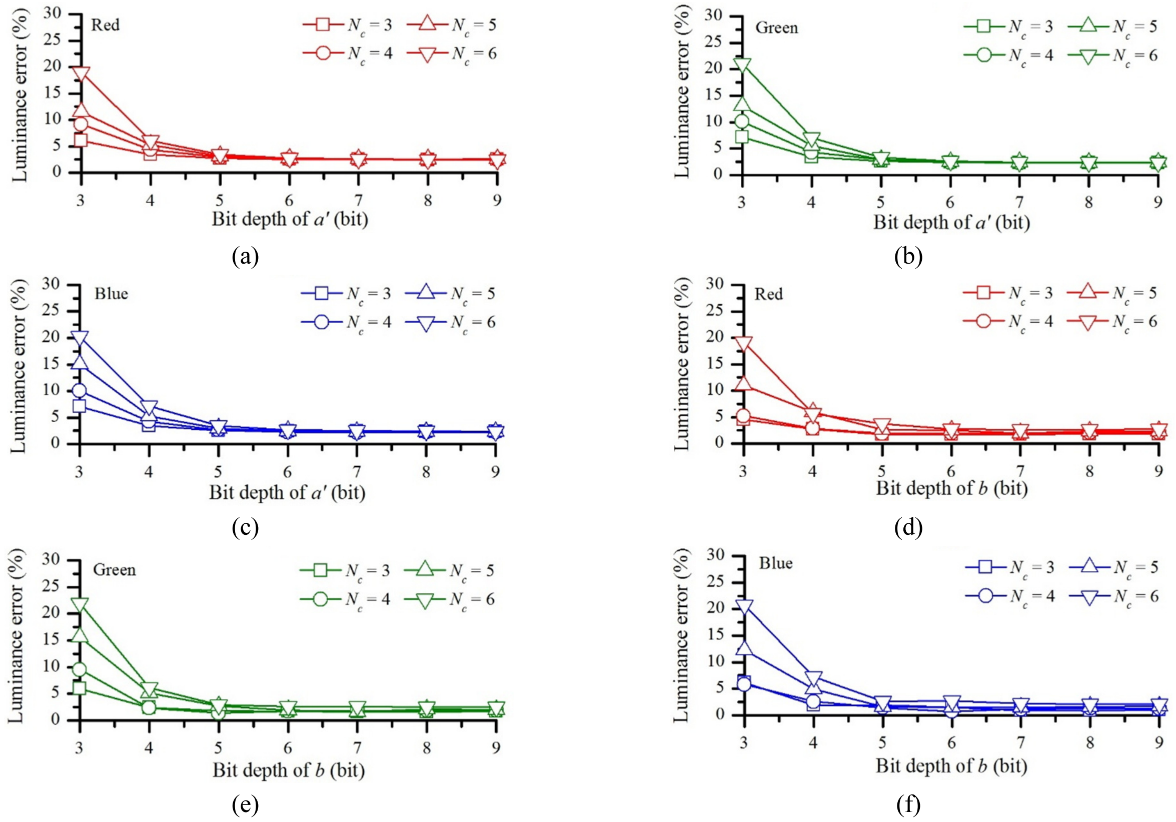


FIG. 6. Compensated luminance error according to the bit depth of a' when b is 6-bit for (a) red, (b) green, and (c) blue colors and of b when a' is 6-bit for (d) red, (e) green, and (f) blue colors for N_c = 3, 4, 5, and 6.

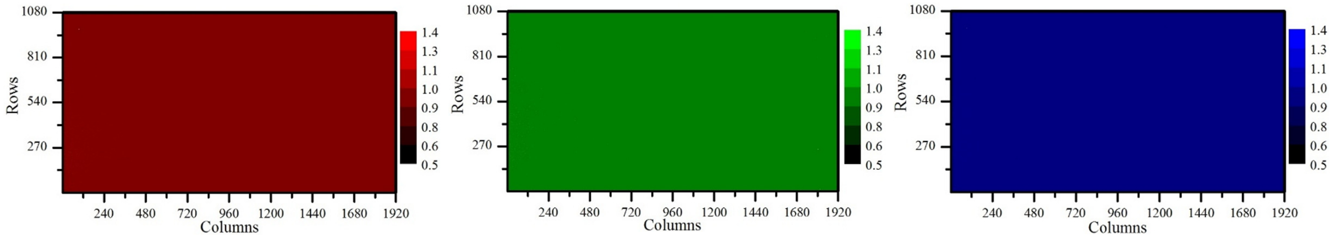
the compensated luminance error according to bit depth of a' when b is a 6-bit and the bit depth of b when a' is a 6-bit, respectively, for N_c = 3, 4, 5, and 6, which yields a higher probability than 3σ. As the range of characteristic parameters for compensation widens, the quantization error of the characteristic parameters increases. When a' and b are greater than 6-bit, the luminance uniformity is not improved by much because the luminance error is saturated. Therefore, a 6-bit is selected as the optimized bit depth of a' and b.

The LUTs for c' are constructed to simplify the calculation of $(g_{in}/255)^{c'}$ using a data modulation logic block, where c' varies from 0.5 to 2 according to the variation in c, and a 15-bit for each g_{in} is used for the LUT to properly represent $(g_{in}/255)^{c'}$.

IV. MEASUREMENT RESULTS

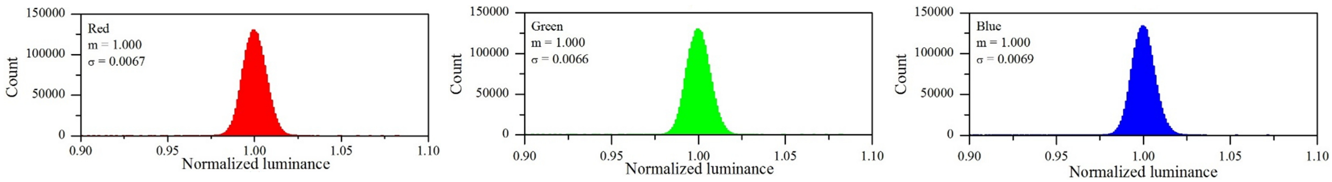
The compensation and driving step was performed using the stored a', b, and LUTs for c' for each color in order to compensate for the non-uniformity of luminance. Since a 6-bit is selected as the bit depth of each characteristic parameter, the required NVM size for a' and b is 6 (bit depth of a' and b) × 1920 (N_{row}) × 1080 (N_{col}) × 3 (number of colors) × 2 (a' and b) = 74.6 Mbits. Also, the required memory size for LUTs for c' is 15 (bit depth of LUT) × 256 (number of gray levels) × 3 (number of colors) = 3,840 bits.

Figures 7 and 8 respectively show the measured normalized luminance of each pixel and the histograms of the normalized compensated luminance of the panel at the 190th gray level with the proposed compensation method. The standard deviations of the normalized luminance are 0.0067, 0.0066, and 0.0069 for red, green, and blue colors, respectively. Considering the 4σ range of luminance, the luminance errors with the proposed compensation method are ± 2.68%, ± 2.64%, and ± 2.76%, which are reduced by 93.06%, 92.73%, and 93.60%, for red, green, and blue colors, respectively, compared to those without the proposed compensation method. As a result, the proposed method with an optimized NVM size dramatically improves the luminance uniformity and reduces the required memory size by 25% compared with prior works in [11, 14] by optimizing the bit depth of the characteristic parameters. As summarized in Table 1, since the required memory size of the characteristic parameters increases with the resolution of the AMOLED panel, optimization of the required memory size is essential to the proposed compensation method of high-resolution AMOLED displays. The performance of the proposed compensation method is compared with that of prior works and summarized in Table 2.



(a) (b) (c)

FIG. 7. The normalized compensated luminance of each pixel at the 190th gray level with the proposed compensation method for (a) red, (b) green, and (c) blue colors.



(a) (b) (c)

FIG. 8. Histogram of the normalized compensated luminance of the panel at the 190th gray level for (a) red, (b) green, and (c) blue colors.

TABLE 1. Required memory size of characteristic parameters according to AMOLED panel resolution and bit depth of parameters

		Full HDTV	UHDTV	
Resolution		1920×1080	3840×2160	7680×4320
Bit depth of parameters	6	74.6 Mbits	299 Mbits	1.29 Gbits
	7	87.1 Mbits	348 Mbits	1.39 Gbits
	8	99.5 Mbits	398 Mbits	1.59 Gbits
	9	112 Mbits	448 Mbits	1.79 Gbits

TABLE 2. Performance of the proposed compensation method compared to that of prior works

Item	[11]	[14]	This work
AMOLED Panel	14.1-inch 1280×720	5.3-inch 800×1280	40-inch 1920×1080
Sensing method	Electrical	Optical	Optical
Uncompensated luminance error	-6.1% ~ 9.0%	-18.1% ~ 8.1%	-43.12% ~ 43.12%
Compensated luminance error	-1.1% ~ 1.2% (white)	-3.8% ~ 3.8% (green)	-2.76% ~ 2.76% (white)
Luminance error reduction ratio*	84.76%	70.99%	93.60%
Required memory per pixel	8 bits × 2	8 bits × 2	6 bits × 2

* Luminance error reduction ratio is calculated as ($\varepsilon_{uncomp} - \varepsilon_{comp}$) / ε_{uncomp}, where ε_{uncomp} and ε_{comp} are uncompensated and compensated luminance error, respectively.

V. CONCLUSION

In this paper, a luminance compensation method using optical sensors for AMOLED displays is proposed. The proposed method compensates for luminance by capturing the luminance of an entire pixel using optical sensors and extracting the characteristic parameters. Then it compensates for the non-uniformity of luminance using a data modulation logic block in the T/CON and an additional NVM. A 40-inch 1920×1080 AMOLED display with a maximum target luminance of 350 cd/m^2 is used to verify the proposed compensation method. The bit depth of the characteristic parameters and total required memory size for the AMOLED panel are optimized to 6-bit and 74.6 Mbits, respectively. The proposed compensation method improves the luminance error from ± 38.64%, ± 36.32%, and ± 43.12% to ± 2.68%, ± 2.64%, and ± 2.76%, which are reduced by 93.06%, 92.73%, and 93.60% for red, green, and blue colors, respectively. Therefore, the proposed compensation method with the optimized memory size is suitable for high image quality and cost-effective large-sized AMOLED display applications.

REFERENCES

1. S. -M. Choi, O. -K. Kwon, N. Komiya, and H. K. Chung, "A self-compensated voltage programming pixel structure for active-matrix organic light emitting diodes," in *Proc. Int'l Display Workshop* (Fukuoka, Japan, Dec., 2003), pp. 535-538.
2. N. Komiya, C.-Y. Oh, K.-M. Eom, Y.-W. Kim, S.-C. Park, and S.-W. Kim, "A 2.0-in. AMOLED Panel with Voltage Programming Pixel Circuits and Point Scanning Data Driver

Circuits," in *Proc. Int'l Display Workshop* (Niigata, Japan, Dec., 2004), pp. 283-286.
3. S.-M. Choi, O.-K. Kwon, and H.-K. Chung, "P-11: An Improved Voltage Programmed Pixel Structure for Large Size and High Resolution AM-OLED Displays," in *SID Int'l Symp. Dig. Tech. Papers* (San Jose, USA, May, 2004), pp. 260-263.
4. N.-H. Keum and O.-K. Kwon, "Pixel structures using the negative feedback method for high-resolution active matrix organic light-emitting diode displays," J. Soc. for Inform. Display **21**, 505-510 (2014).
5. C.-H. Ho, C. Lu, and K. Roy, "An Enhanced Voltage Programming Pixel Circuit for Compensating GB-Induced Variations in Poly-Si TFTs for AMOLED Displays," IEEE J. Display Technol. **10**, 345-351 (2014).
6. Y. Kim, J. Kanicki, and H. Lee, "An a-InGaZnO TFT Pixel Circuit Compensating Threshold Voltage and Mobility Variations in AMOLEDs," IEEE J. Display Technol. **10**, 402-406 (2014).
7. Y. Kim, Y. Kim, and H. Lee, "A Novel a-InGaZnO TFT Pixel Circuit for AMOLED Display With the Enhanced Reliability and Aperture Ratio," IEEE J. Display Technol., vol. **10**, 80-83 (2014).
8. H.-J. In and O.-K. Kwon, "External Compensation of Nonuniform Electrical Characteristics of Thin-Film Transistors and Degradation of OLED Devices in AMOLED Displays," IEEE Electron Device Lett. **30**, 377-379 (2009).
9. U.-G. Min and O.-K. Kwon, "Real-time external sensing and compensation method for organic light emitting diode displays," Electronics Lett. **45**, 1232-1234 (2009).
10. U.-G. Min, H.-J. In, and O.-K. Kwon, "A real time video data adjusting method for active matrix organic light emitting diode displays with high image quality," IEEE Trans. Consumer Electronics **55**, 2372-2376 (2009).
11. H.-J. In, K.-H. Oh, I. Lee, D.-H. Ryu, S.-M. Choi, K.-N. Kim, H.-D. Kim, and O.-K. Kwon, "An Advanced External Compensation System for Active Matrix Organic Light-Emitting Diode Displays With Poly-Si Thin-Film Transistor Backplane," IEEE Trans. Electron Devices **57**, 3012-3019 (2010).
12. T. Kohno, T. Kuranaga, H. Kageyama, M. Ishii, N. Kasai, N. Nakamura, and H. Akimoto, "LTPS AM-OLED Display Consisting of Two-TFTs/One-Capacitor Pixel Circuits for Producing High-Uniformity Images," IEEE Trans. Electron Devices **60**, 3780-3786 (2013).
13. H.-J. In, K.-H. Oh, O.-K. Kwon, C. H. Hyun, and S.-C. Kim, "A luminance adjusting algorithm for high resolution and high image quality AMOLED displays of mobile phone applications," IEEE Trans. Consumer Electronics **56**, 1191-1195, (2010).
14. K.-H. Oh, N.-H. Keum, and O.-K. Kwon, "Memory reduction method of luminance compensation algorithm for mobile AMOLED display applications," in *Proc. IEEE Int'l Conf. on Consumer Electronics 2013* (Las Vegas, USA, Jan., 2013), 389-390.
15. D. W. Marquardt, "An Algorithm for Least-Squares Estimation of Nonlinear Parameters," J. Soc. Ind. and Appl. Mathematics **11**, 431-441 (1963).
16. B. Iñiguez, Z. Xu, T. A. Fjeldly, and M. S. Shur, "Unified model for short-channel poly-Si TFTs," Solid-State Electronics **43**, 1821-1831 (1999).
17. B. Iñgueza, R. Picosb, D. Vekslerc, A. Koudymovc, M. S. Shurc, T. Ytterdald, and W. Jacksone, "Universal compact model for long- and short-channel Thin-Film Transistors," Solid-State Electron. **52**, 400-405 (2008).